Renewable and Sustainable Energy Reviews 21 (2013) 365–370

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Small-compressed air energy storage system integrated with induction generator for metropolises: A case study

F. Baqari, B. Vahidi *

Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 19 September 2011
Received in revised form
24 December 2012
Accepted 26 December 2012
Available online 9 February 2013

Keywords:
Compressed air energy storage
Induction generator
Wind turbine

ABSTRACT

A case study of small-compressed air energy storage (S-CAES) system in Iran metropolises is discussed in this paper. It proposes an alternative way of clean energy storage for electronic and electrical devices. It will present a hybrid technology for a renewable energy power generation; which is developed as a small scaled power plant. There are various forms of storing energy and the applications of performance requirements. This work provides a feasibility study of S-CAES system to support electricity power of metropolis areas. Classification of S-CAES implementation is made on the basis of available energy, power output and energy efficiency. The most important parameters in this category are the efficiency, output power, enough capacity and so on. This paper concentrates on technical implications. The S-CAES work's at low pressure and this make it easy to use in metropolises.

Contents

1. Introduction

The generating capacity of wind energy facilities has grown rapidly in recent years; in 2008 alone, the U.S. wind industry added over 8,500 MW of generating capacity. In 2009 it increases up to 10 MW and in 2010 they added 5 MW and finally in 2011 increase attained around 7 MW, it bringing total U.S. wind installations to 46919 MW at the end of the 2011 [1]. As wind energy generation continues to penetrate the grid at increasing levels, the inherent variability in the wind requires additional standby reserves to compensate for low wind energy production during peak load. These standby reserves are traditionally gas turbines, which have a low startup time and operational cost. However, the recent growth of the wind industry and national targets to reach upwards of 20% grid penetration may require additional options to offset the effects of wind's variable output and supply a base load generating capacity. Energy storage, particularly CAES, provides a possible solution to help address the challenges of increased grid penetration of wind energy [2]. However more economical and more efficient energy storage systems are needed. There is some debate about whether renewable energies can provide a fix power in a fix period, Is energy storage critical now?

Energy storage greatly enhances these two missions by:

- Increasing load factors of renewable power sources by storing energy produced by renewables when demand and energy price are low and releasing it when demand and energy price are high.

* Corresponding author. Tel.: +98 21 64543330; fax: +98 21 66406469.
E-mail address: vahidi@aut.ac.ir (B. Vahidi).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.12.040

- By more fully utilizing off-peak power plants (solar, wind and coal plants) and reducing load factors of peaking power plants that are based on the fuel oil and natural gas.

Energy storage significantly improves operations and reliability of power grids providing arbitration and regulation and synchronous reserve services via rapidly providing power when suddenly needed. Fig. 1 demonstrates different models of storage system. It may indeed be true to say that Compressed Air Energy Storage (CAES) is going to be one of the most popular ways in the new millennium because of its vast output power level and its high discharge duration in comparison with other systems [3]. This storage system has long service period, low cost of energy, low cost of maintenance and operation and high power efficiency. There are currently two installed CAES facilities: a 290 MW facility in Huntorf, Germany and a 110 MW facility in McIntosh, Alabama. [4,5]. On the other hand another facility Norton, Ohio is under development with 2000 MW generation capacity [6]. This technology may potentially allow wind energy to penetrate the grid at a higher percentage and, depending on available technology and suitable geology, may provide a low cost solution for energy storage. CAES facilities can be developed in pre-existing geological formations and operate with less fuel than a traditional gas turbine. This creates the opportunity to manage on/off-peak energy and to possibly turn variable wind generation into a consistent base load power source.

Moreover these days, distributed generation is going to be more common and effective. The argument put forward is that a good solution to decrease energy cost is to use renewable energies whenever it is possible. In this paper a case study is presented that is based on smart power electricity switch (see Fig. 2), in this method customer has a multi feed storage system, both distribution line and wind turbine (or other renewable energy converter) are connected to a smart clutch and the output is connected to an induction motor/generator, this induction motor (IM) is connected to a compressor. Whenever wind speed is high enough wind turbine connect to IM and it turns compressor. On the other hand in off-peak period of electricity market when demand and energy price are low IM would be connected to distribution line. Smart clutch connects more economic source to the motor and it turns the compressor and feed air bank. Whenever the customer needs electricity power expander connects with a clutch to induction Generator (IG) and compressed air expand in expander and it turns IG. This procedure makes reliable, low cost electricity power. The S-CAES system is operated in low pressure (not more than 10 bars), so it can be used everywhere that other parameters are noticeable [7,8]. There are three main stages, compression stage, storage stage and expansion stage.

2. Thermodynamic analysis

2.1. Kinetic-to-electrical energy conversion

In fact, kinetic energy of air movement over the earth is calculated by (1). The mass of air stream is equal to ρv and wind speed is shown by V_m. Also ρ is air density and v is volume of air

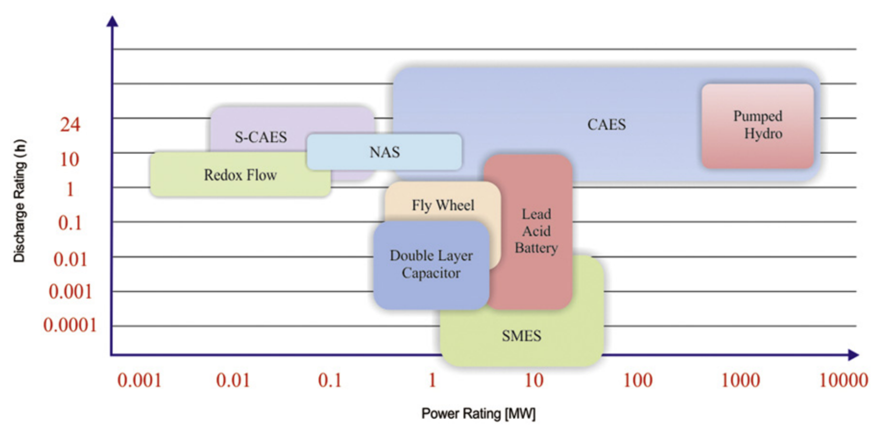

Fig. 1. Storage systems properties.

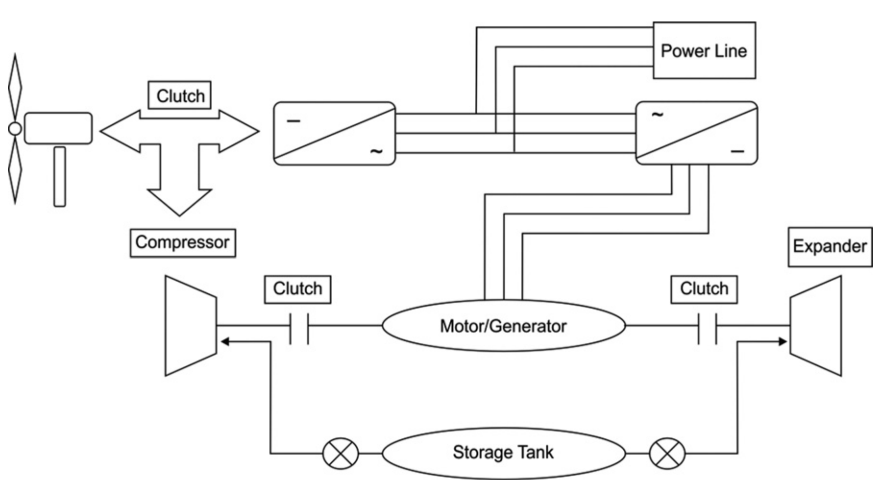

Fig. 2. S-CAES multifeed generator.

stream which is like a virtual cylinder [9].

$$E = \frac{1}{2}\rho v V_m^2 \quad (1)$$

Wind power depends on wind volume which defines by wind speed and effective area. The air density could be taken 1.224 kg/m^3. Wind power coefficient C_p is another important parameter. In this mechanical instrument wind power would not be converted completely to mechanical power (shaft output) so generated power is calculated as [10]:

$$P_w = \frac{1}{2} C_p \rho V_m^3 A \quad (2)$$

Theoretically, $C_p \le 0.593$ which is known as Betz limit. Actual values will probably lie between 25% to 30%. This will vary with wind speed, with the type of turbine and with the nature of load [11,12].

$$C_p \le 0.3 \quad (3)$$

Mechanical power of generator shaft comes from wind power but electrical efficiency η_g and mechanical efficiency η_m of this conversion are effective. The output power is P_e.

$$P_e = \eta_m \eta_g P_w \quad (4)$$

Consider these results in real condition of Iran main metropolises. Fig. 3 shows average level of wind speed in Tabriz for a year.

Table 1 leads us to Fig. 4 that illustrates electrical power which would be generated by S-CAES. Incontrovertibly, this generation potential is perfect.

Table 1 demonstrates potential of power production in this method in some of Iran metropolises.

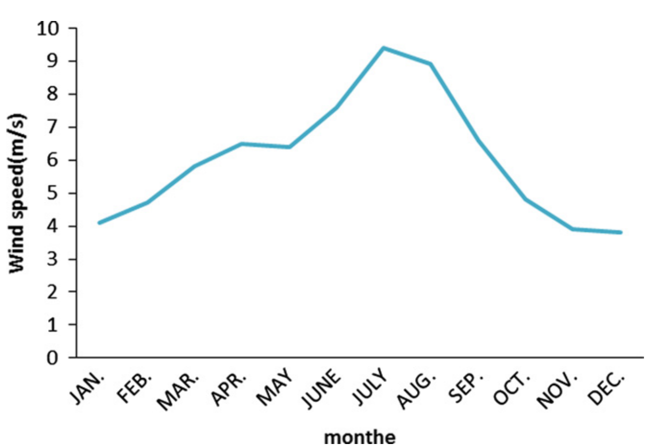

Fig. 3. Tabriz wind speed multiline bar.

Table 1
Potential of generation electrical power (w h).

	Esfahan	North of Tehran	Manjil	Yazd	Tabriz	Mashhad	Shiraz
JAN.	**2.3345**	**0.14154**	**18.68**	**8.46**	**7.33**	**2.33**	**4.56**
FEB.	**9.05892**	**0.522475**	**50.47**	**14.11**	**11.04**	**5.39**	**10.35**
MAR.	**21.8411**	**0.85076**	**106.35**	**19.70**	**20.75**	**11.04**	**17.69**
APR.	**22.9706**	**1.86913**	**153.44**	**24.14**	**29.20**	**11.04**	**17.69**
MAY	**16.7456**	**2.09319**	**267.5**	**25.36**	**27.88**	**10.35**	**20.75**
JUNE	**10.3512**	**1.2939**	**813.05**	**19.70**	**46.683**	**14.95**	**15.83**
JULY	**9.05892**	**0.6202**	**929.651**	**24.14**	**88.3287**	**18.68**	**13.29**
AUG.	**6.3083**	**0.6202**	**764.52**	**16.75**	**74.9702**	**12.51**	**10.35**
SEP.	**3.48472**	**0.7294**	**443.8**	**9.7**	**30.5739**	**7.88**	**7.88**
OCT.	**2.87132**	**0.7294**	**116.21**	**6.31**	**11.7609**	**4.56**	**5.83**
NOV.	**1.66165**	**0.2336**	**18.68**	**5.39**	**6.3083**	**2.09**	**3.82**
DEC.	**1.47012**	**0.1063**	**11.04**	**6.81**	**5.83538**	**1.66**	**3.48**

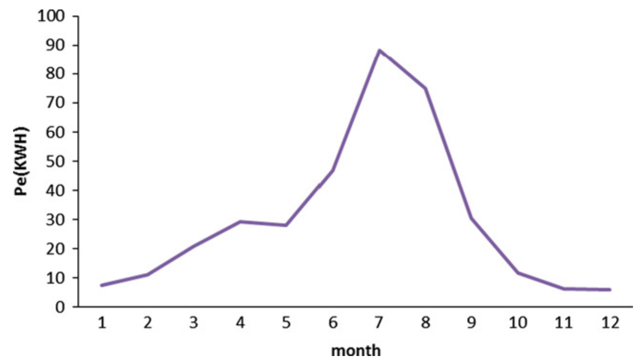

Fig. 4. Potential of generating electrical power in Tabriz (kW h).

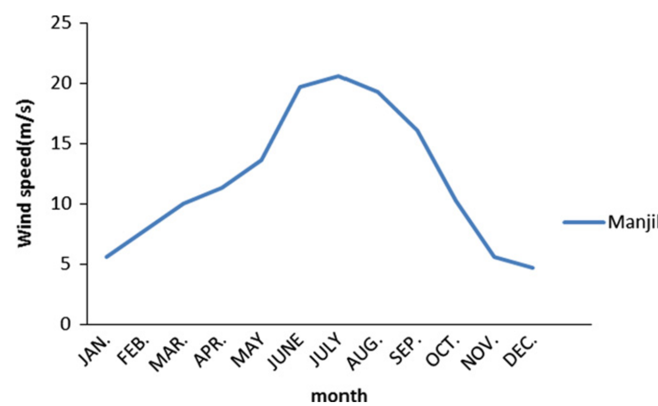

Fig. 5. Manjil wind speed multiline bar.

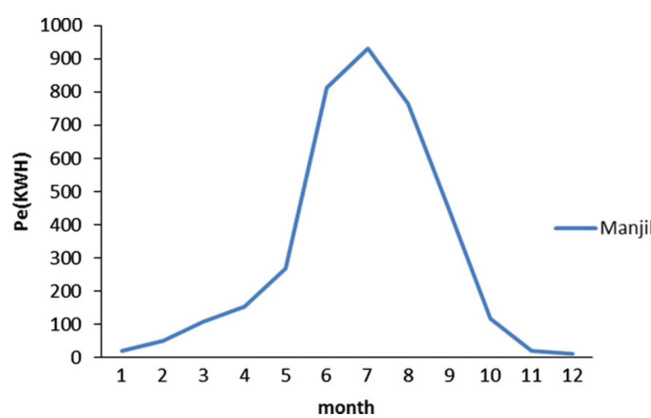

Fig. 6. Potential of generating electrical power (kW h) in Manjil.

"Iran's wind energy market has not yet realized its potential. The mountainous landscape of Iran holds unique wind corridors and preliminary studies have shown an estimated practical wind power potential of at least 6500 MW" [13].

"Iran's best wind resources are located in the mountainous part of the country, along the Alborz and Zagros mountain chain" [13].

Manjil is one of these areas. It has high speed winds in each month of the year. Fig. 5 shows Manjils wind speed in several months of year, and Fig. 6 shows its high potential to generate electrical power in big scale CAES power plant.

2.2. Compression process

The CAES system consists of a compressor for changing the air into the reservoir and a turbo expander as presented on Fig. 2. An induction motor/generator is connected through clutches to the

compressor and turbine. While in the charging mode the motor which is used off-peak or wind power drives the compressor to inject the air into the reservoir. During consumption periods, the CAES system is operated in the discharging mode. Then, the compressed air is released from the reservoir to expander and it expands through a turbine that drives a generator to provide needed power. Air is assumed to be perfect gas which specific heat is constant. The ideal gas law relates the pressure P, the volume V, amount of substance in the air, ideal gas constant and temperature T of a gas as follows.

$$PV=mRT \tag{5}$$

By the definition of work, where (1) and (2) are the initial and final status of the system [14]

$$W=-\int_{v_2}^{v_1} P dv \tag{6}$$

$$W=-\int_{v_1}^{v_2} \frac{nRT}{V} dv \tag{7}$$

$$W=nRT(LnV_1-LnV_2)=nRT(LnP_2-LnP_1)=P_1V_1(LnP_2-LnP_1) \tag{8}$$

where P_1 and P_2 and V_1, V_2 are the pressure and the volume of the initial state and final state. Initial state is atmospheric state and final state is compressed state. Obviously power is work per unit time; on the other hand the air flow is volume per unit time. So compression power is equal to

$$P_c=P_1Q(LnP_1-LnP_2) \tag{9}$$

The work for producing the compressed air as polytrophic process is shown as

$$W=\frac{\gamma}{\gamma-1}P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}-1\right] \tag{10}$$

where P_1 and P_2 and V_1, V_2 are the pressure and the volume of the initial state and final state. Initial state is atmospheric state and final state is compressed state.

$$P_c=\frac{\gamma}{\gamma-1}P_1Q\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}-1\right] \tag{11}$$

$$\gamma=\frac{C_p}{C_v} \tag{12}$$

Notice that (P_2/P_1) is the compression ratio [15]. The result of Eqs. (2), (4) and (11) is

$$Q=\frac{0.5\times C_p\eta_m\eta_g\rho V_m^3 A}{\gamma/(\gamma-1)P_1[(P_2/P_1)^{(\gamma-1)/\gamma}-1]} \tag{13}$$

Depending on wind turbine and wind speed parameters the air flow is shown in Fig. 7. In this single line graph Tabriz wind speed and compression ratio are considered.

The total energy efficiency is

$$\eta=\frac{P_c}{P_w}=\frac{(\gamma/(\gamma-1))P_1Q_1\left[(P_2/P_1)^{(\gamma-1)/\gamma}-1\right]\eta_s}{0.5C_p\rho V_m^3 A} \tag{14}$$

η_s is the efficiency of compressor and compressed air generator. The total efficiency of this system in Tabriz is illustrated in Fig. 8.

2.3. Air storage stage

In underground storage mechanical and thermal parameters are the most important and effective parameters that should be considered in calculations [15].

$$\frac{dT}{dt}=\frac{1}{m}\left(1-\frac{1}{k}\right)(m_{in}T_{in}-m_{out}T_{out})+\frac{\alpha A_w(T_w-T)}{mC_p} \tag{15}$$

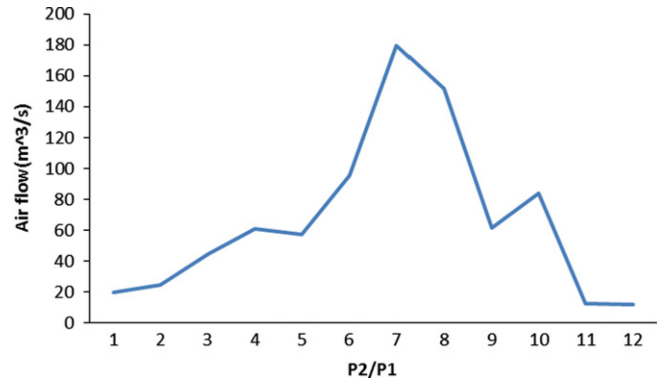

Fig. 7. Air flow.

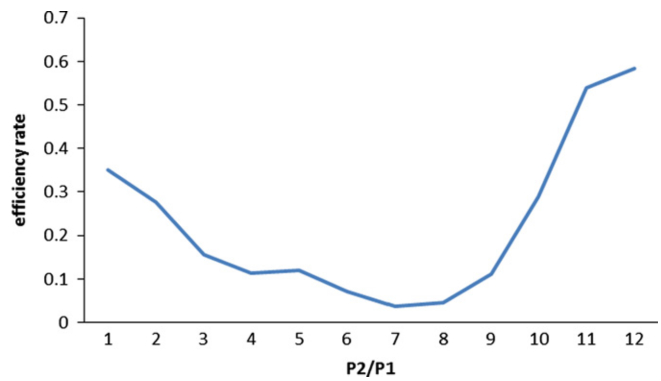

Fig. 8. Total efficiency.

K is the ratio of specific heat capacity in constant pressure and constant volume ($k=C_p/C_v$). A_w is wall's temperature surface that is in contact with cavern air and T is the air temperature, T_w is the wall's temperature that can be effective on air temperature.

2.4. Expansion stage

Expansion equations are similar to compression stage, the power that is making by expansion stage is equal to

$$P_t=\eta_t m C_p T_{in}\left(1-\left(\frac{P_2}{P_1}\right)^{\gamma/(\gamma-1)}\right) \tag{16}$$

where η_t is the expansion stage efficiency and m is the mass of air flow in this stage and T_{in} is the inlet air of expander temperature [15].

3. DQ induction generator model

In many cases, analysis of induction motors with space vector model is complicated due to the fact that we have to deal with variables of complex numbers. For any space vector Y, define two real quantities S_q and S_d as

$$S=S_q-jS_d \tag{17}$$

In other words, $S_q=\mathrm{Re}(S)$ and $S_d=-IM(S)$. Fig. 9 demonstrates the relationship between d–q axis and complex plane on a rotating frame with respect to stationery a–b–c frame.

Each variable (voltage, current or flux linkage) in the synchronous frame is stationary and fixed to a constant magnitude in steady state. Dynamic d–q equivalent circuit is shown in Fig. 10 [16,17].

$$V_{qs}=R_sI_{qs}+p\lambda_{qs}+\omega_s\lambda_{ds} \tag{18}$$

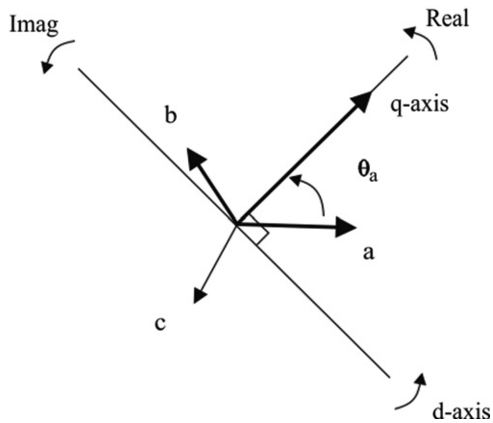

Fig. 9. Definition of *d*-axis and *q*-axis.

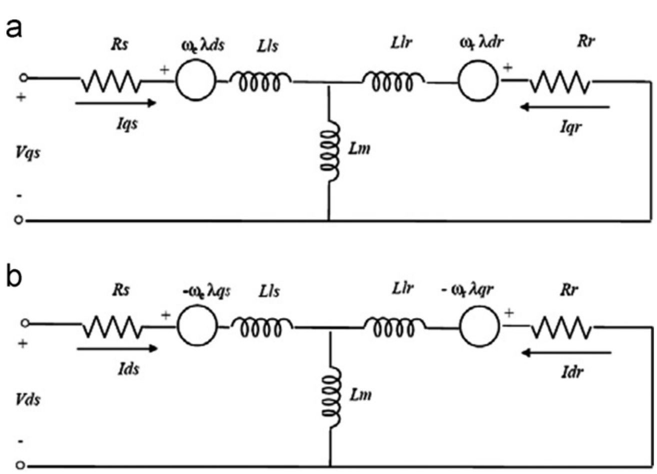

Fig. 10. *d*–*q* equivalent circuit on a synchronous frame.

$$V_{ds} = R_s I_{ds} + p\lambda_{ds} + \omega_s \lambda_{qs} \tag{19}$$

$$0 = R_r I_{qr} + p\lambda_{qr} + \omega_r \lambda_{dr} \tag{20}$$

$$0 = R_r I_{dr} + p\lambda_{dr} + \omega_r \lambda_{qr} \tag{21}$$

where flux linkage variables are define by

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \tag{22}$$

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \tag{23}$$

$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \tag{24}$$

$$\lambda_{dr} = L_m I_{ds} + L_r I_{dr} \tag{25}$$

$$T_e = \frac{3}{4} P \left(\frac{L_m}{L_r}\right) \{I_{qs}\lambda_{dr} - I_{ds}\lambda_{qr}\} \tag{26}$$

Mechanical equivalent of this machine is

$$T_e + T_m = J\frac{d\omega_m}{dt} \tag{27}$$

T_m is mechanical torque of generator shaft and T_e is Electromagnetic torque of machine also ω_m is rotational speed of shaft [18]. Obviously T_m comes from power equation

$$P_m = T_m \omega_m \tag{28}$$

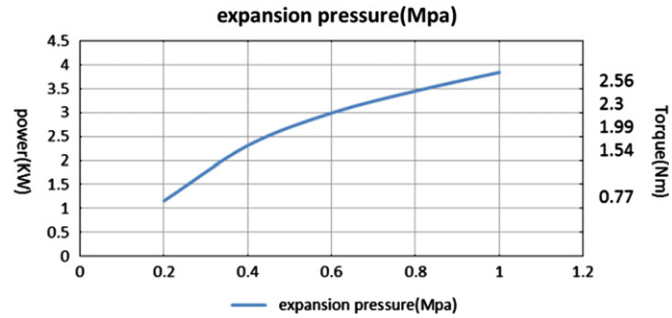

Fig. 11. Connection between expansion pressure and power and torque.

4. Conclusion

In recent years different energy storage techniques have been developed. Among them the compressed air energy storage (CAES), proposed here, to be used in conjunction with induction generator shows promising performance. This system is effective for metropolises. It can be a useful distributed generation source instead of high price electricity power of power plants. To put everything in a nut shell, the simulation results show that, S-CAES is useful to produce a building required energy along the year especially in Tabriz. The compression pressures and wind speed directly depend on air flow, efficiency and mechanical torque of generator; moreover it mirrors good efficiency of S-CAES in this scale and perfect output power of this system.

Our research demonstrates good efficiency of S-CAES in this scale and perfect output power of this system. It goes without saying that S-CAES in pressure ratio from 3 to 9 is not noticeable for Tabriz but after 10 it seems perfect. This shows S-CAES with pressure ratio over the 9 in Tabriz is entirely beneficial (see Fig. 8).

The compression pressures and wind speed directly depend on air flow and efficiency and mechanical torque of generator (see Fig. 11).

This system can apply to build uninterruptible power supply, peak shaving and reduce technical loss of power grids. It can be a good substitution for electricity distribution lines in some of Iranian metropolises.

References

[1] Global wind report, GWEC; 2011, pp. 63–5.
[2] Compressed air energy storage engineering and economic study. Final report, New York State Energy Research and Development Authority; 10–09 Dec 2009 pp. 6–1.
[3] Daniel, Roy. Energy storage and power LLC, Compressed air energy storage scoping workshop, Columbia University; Oct 2008. pp. 101–40.
[4] Crotogino, Fritz, Mohmeyer, Kluse-Uwe Scharf, Dr.Roland. Huntorf CAES more than 20 years of successful operation, In: Spring 2001 meeting Orlando, FL, USA; 15–18 April 2001.
[5] Enis, Dr.Ben, Lieberman, Dr.Paul Rubin, Mr.Irving. Transportable compressed air energy storage (T-CAES) system driven by a 2500 kW wind turbine. In: Proceeding of international conference on efficiency, cost, optimization, simulation and environment impact of energy system; 2006.
[6] Haddington sells rights to its Norton Energy Storage project to FirstEnergy. PR Newswire, 〈http://www.prnewswire.com/news-releases/haddington-sells-rights-to-its-norton-energy-storage-project-to-firstenergy-71572382.html〉 (last accessed 20.12. 2012).
[7] Vongmanee Varnin, Monyakul Veerapol. A new concept of small-compressed air energy storage system integrated with induction generator. International Conference on System Engineering and Technology 2008:866–71.
[8] Cai Maolin, Kawashima, Kagawa Toshiharu. Power assessment of flowing compressed air. Transactions of the ASME 2006;128(2):402–5.
[9] Vongmanee, Varin, Monyakul, Veerapol. A modeling of self-excited induction generators driven by compressed air energy storage based on field oriented control principle. In: 2nd IEEE international conference on power and energy (PE Con 08); December 1–3,2008. pp. 834–8.
[10] Mathew Sathyajith. Wind Energy fundamentals, resource analysis and economics. Springer; 2006.
[11] Valtchev, Ventzislav, Automous renewable energy conversion system, Renewable Energy, 19, 259–75.

[12] Eric-Hau. Wind turbines fundamentals technologies application economics. 2nd ed. NC: Springer; 2006 pp. 485–532.
[13] Global wind Report. GWEC; 2010. pp. 46–7.
[14] Vongmanee, Varin, Monyakul, Veerapol, A modeling of small compressed air energy storage (small-CAES) for wind energy storage applications, In: GMSARN international conference on sustainable: issues and prospects for the GMS, November 12–14; 2008.
[15] Steta, Fernando De Samaniego Modeling of an advanced adiabatic compressed air energy storage (AA-CAES) unit and an optimal model-based operation strategy for its integration into power markets. Master thesis. PSL2003, Zurich, Oct 2010.
[16] Novotny DW, Lipo TA. Vector control and dynamics of AC drives. Oxford: Clarendon Press; 1997.
[17] Chee-Mun-ong. Dynamic simulation of electric machinery. Prentice Hall PTR; 1997.
[18] Ohm, Dal Y, Dynamic model of induction motors for vector control, 〈www.drivetechinc.com/articles/IM98VC1.pdf〉 (last accessed 20.12.2012 2012).